Consideration of Multi-Phase Criterion in the Differential Protection Algorithm for High-Impedance Grounded Synchronous Generators

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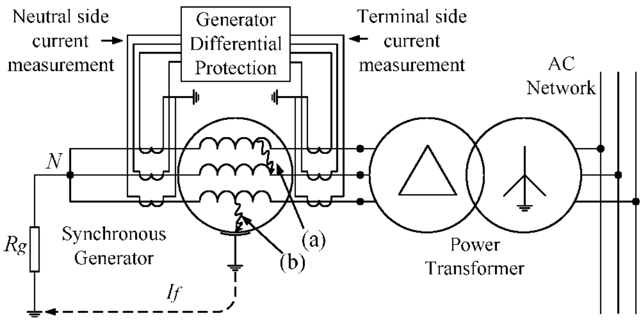

Figure 1. Simplified scheme of power plant with generator differential protection. Stator phase-to-phase fault (a), and stator ground fault (b) are indicated.

I. INTRODUCTION

Protective Systems are nowadays primary concerns for the correct and reliable operation of power plants. Currently, numerical protective systems allow protecting power generators against a large list of events, which could imply severe damage not only for the generator, but also for the whole power plant. Differential Protection (commonly known as 87 [1]) is one of the most important protection function. This electrical protection is based on the detection of differential current between the input current and the output current of the circuit under protection [2]. The correct operation of the differential protection is a very relevant research topic, not only related to generators, but also related to transformers [3] and bus bars. This is because of the effects of the saturation of Current Transformers (CTs), wrong selection of CTs [4], or CT burden unbalances, in the correct operation of this electrical protection. The saturation of current transformers can be produced by long lasting DC component, large AC currents, or the addition of both phenomena, and these may imply unwanted trip commands [5]. In some cases, saturation can appear under relatively small currents (under twice the rated current) because of the CT burden unbalances, or because the neutral-side CTs and terminal-side CTs may come from different manufacturers [6]. The neutral-side CTs are generally supplied by the generator manufacturer, while the terminal-side CTs are supplied by the switchgear manufacturer. Inaccurate selection of CTs, or re-utilization of those for inappropriate applications, may also cause the mentioned saturation problem.

The generator differential protection is based on the measurement of the current obtained as the difference between the current at neutral side and the current at terminal side of each phase (Fig. 1). According to this, if any fault makes those currents to be different at any phase, the protective system will detect differential current and, if this current exceeds the setting value, the generator breaker, the field breaker, and in many cases the turbine, will be tripped. Considering the relevance of this electrical protection, avoiding unwanted trip commands is very important. Due to its operation principle, 87 is used for protecting the stator winding against phase-to-phase (Fig. 1, (a)), or three-phase faults. Furthermore, in low-resistance grounded generators, the differential protection can detect stator earth-faults, as in this case the neutral current has a high value, and it is directly measured as differential current in the stator phase under faulty conditions. High power synchronous generators are commonly grounded by an impedance of high value, when there is one generation unit connected to the step-up transformer [2]. In this case, the earth-fault current (I_f) is limited to 5A or 10A, by the high value of the grounding resistance (Fig. 1, (b)). Therefore, the detection of stator earth-fault, using 87G, is not possible, as the differential current is negligible compared to the rated current of generators. According to this, the operation of the differential protection due to the detection of differential current at only one phase of the stator winding makes no sense. Phase-to-phase faults imply the appearance of differential current at least in two phases.

Many cases have been reported, where 87 has tripped while there is not any phase-to-phase fault, and registers show that the differential current is only measured at only one phase. This phenomenon is usually caused, as described, by CT saturation, or constructive differences between CTs of terminal and neutral sides, due to the fact they come from different manufacturers. Multi-phase criterion needs to be applied to the conventional differential protection algorithm in order to avoid these undesired trips.

This paper is structured as follows: Section II describes briefly the conventional characteristic of the differential protection. The multi-phase criterion, applied to differential protection algorithm, and the evaluation of this operation principle in real sample test results are described in Section III and Section IV, respectively. Finally, some setting considerations are given in Section V.

II. DIFFERENTIAL PROTECTION ALGORITHM

The commonly used differential protection algorithm is based on a dual slope characteristic, or multiple slope characteristic, as shown in Fig. 2, where I_d is the differential current, which can be obtain using expression (1). The restraining current, I_b, is obtained using different expressions, depending on the manufacturer, but the most commonly used expression is shown in (2), where T and N denotes terminal side and neutral side respectively, $\vec{\ }$ means phasor magnitude and | | the module.

$$I_d = \left|\vec{I}_T - \vec{I}_N\right| \tag{1}$$

$$I_b = \frac{\left|\vec{I}_T\right| + \left|\vec{I}_N\right|}{2} \tag{2}$$

For obtaining correctly I_d and I_d, numerical protective systems filter digitally the input currents, and obtain the phasor magnitudes using Fourier filters.

Setting parameters I_{s1}, I_{s2}, K_1 and K_2, are commonly used for defining the operation zone. According to this, the differential protection operates if I_d exceeds the operation current, I_{op}, given by (3).

$$I_{op} = \begin{cases} I_{s1} & I_b \le I_{s1}/K_1 \\ K_1 \cdot I_b \qquad \text{if} & I_{s1}/K_1 < I_b \le I_{s2} \\ K_1 \cdot I_{s2} + K_2 \cdot (I_b - I_{s2}) & I_b > I_{s2} \end{cases} \tag{3}$$

Generally, the dual slope characteristic achieves stability in case of external faults, when the large value of the currents causes AC saturation, and long lasting DC component of these currents cause DC saturation. These events can be taken into account by the correct setting of K_1 and K_2, as in case of

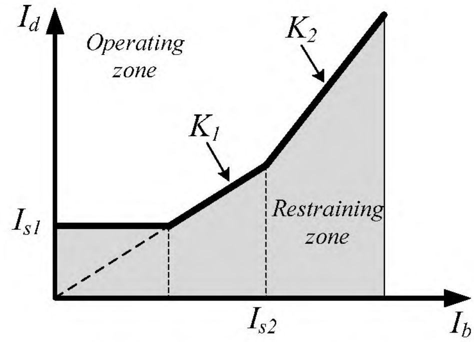

Figure 2. Common Differential Protection Algorithm

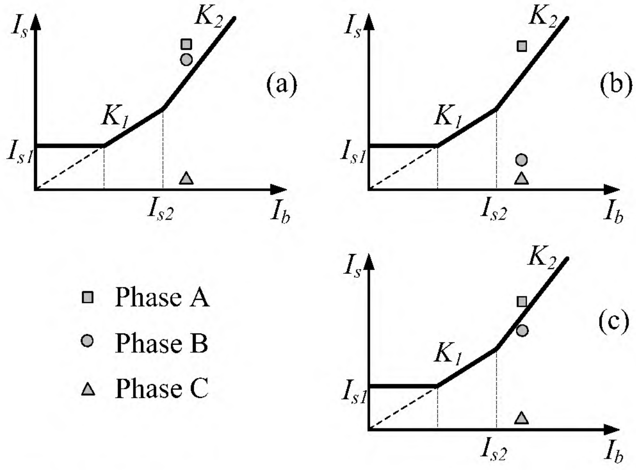

Figure 3. Tripping cases

external faults the restraining currents have high value ($I_b > I_{s2}$).

In presence of magnetizing inrush currents, restraining currents increase rapidly, evolving as an external fault, and it starts to decrease at very low value (lower than twice the rated current). In this process, an individual CT may saturate, causing the appearance of differential current in only one phase. This phenomenon cannot be solved increasing the slope setting values, as this event occurs in the restraining range close to the rated current, where the operation current is lower.

III. MULTI-PHASE CRITERION FOR DIFFERENTIAL PROTECTION ALGORITHM

As described, in synchronous generators grounded by high value resistance, differential protection cannot detect stator earth-faults as fault current is limited to 5 A or 10 A. According to this, phase-to-phase faults imply the existence of differential current in at least two phases of the generator. In principle, generator differential trip commands must not be considered if there is differential current in only one phase. Some manufacturers obtain the restraining current as the maximum of the restraining current of the three phases, during the last power system cycle. In this way, restraining current is blocked during the transient process until every restraining current decrease. Multi-Phase Criterion is needed during the first cycles of the saturation process as the differential current at the phase under saturation may increase over the operation current while the restraining current is blocked at a low value.

In Fig. 3(a), the value of differential current and restraining current are represented at the instant of the trip command in case of internal phase-to-phase fault. In this situation, the differential current of two phases has a value which exceeds the operation current. Both phases have similar value of differential current.

In case of external fault with CT saturation at any individual phase, the differential current can exceed the operation current, while the values at the remaining phases are much lower (Fig. 3(b)).

However, the trip command of 87 should not be limited to the cases in which the differential current exceeds the operating current in two or three phases as, in this case, the operation of the differential protection will be strongly dependent of the correct and precise setting of the characteristic parameters. In some cases of internal phase-to-phase stator fault, the value of one of the Id may be very close to the operation current, but still under it (Fig. 3(c)). These situations can be caused by the effect of CT saturation at early stage in any phase. These cases are very exceptional, but they have to be considered if a multi-phase criterion is implemented.

In Fig. 4, the general differential protection algorithm is shown. First, the common setting parameters, I_{s1}, I_{s2}, K_1 and K_2, are entered to the algorithm block. $I_{b,k}$ and $I_{d,k}$ are the instantaneous restraining current and differential current at phase k, where k correspond to any phase A, B or C. If $I_{d,k}$ exceeds the operation value, the differential protection condition (DIF) is fulfilled, and the differential flag “state1” ($I_{dk,st1}$) is activated (4).

$$I_{dk,st1} = \left(I_{d,k} > I_{op}\right) \tag{4}$$

In Fig. 5, the differential protection algorithm is evaluated using the secondary settings, I'_{s1}, I'_{s2}, K'_1 and K'_2, that define the interception band. In this case, the differential flag “state2” ($I_{dk,st2}$) is only activated if, at least, two of the phases exceed the secondary operation current (5).

$$I_{dk,st2} = \left(I_{d,k} > I'_{op}\right) \text{ AND } \left(I_{d,k^*} > I'_{op}\right) \tag{5}$$

Where I'_{op} is the operation current using the secondary settings, and k^* represents a phase different than phase K. In this way, exceptional cases are included.

Generator 87 operation is only allowed if Multi-Phase condition (MP) is fulfilled (6).

$$MP = \left(I_{dk,st1}\right) \text{ AND } \left(I_{dk,st2}\right) \tag{6}$$

This algorithm doesn’t add a delay in the differential protection algorithm since, considering the damage that the real internal phase-to-phase stator faults cause in generators, this is widely undesired and not recommended.

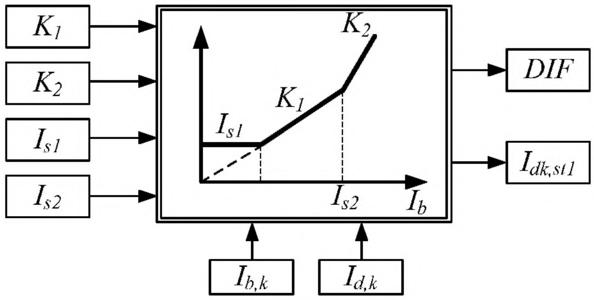

Figure 4. Common Differential Protection Algorithm

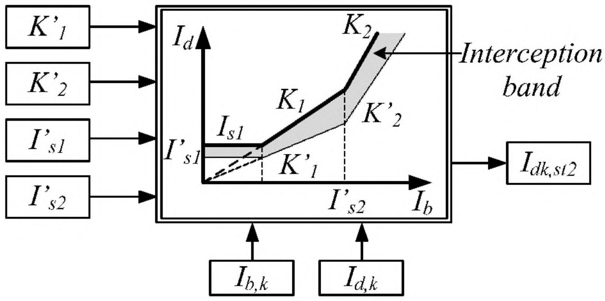

Figure 5. Multi-Phase Criterion based on interception band

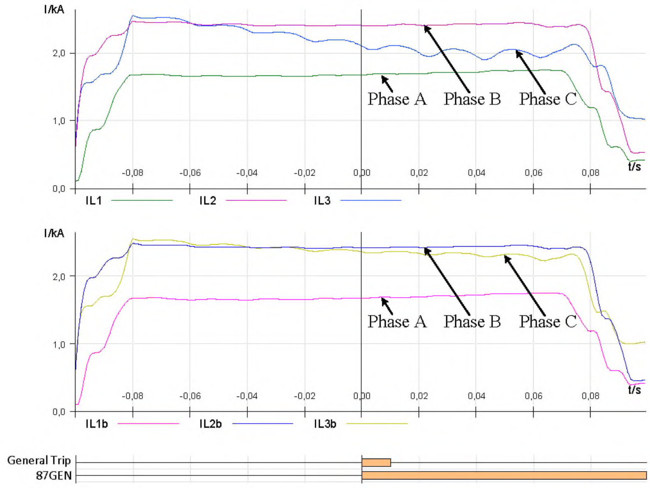

Figure 6. Neutral side currents (top) and terminal side currents (bottom) in rms value.

IV. Sample Test Results

Several cases of false trip commands of differential protection have been reported in the last years from different power plants. In some of these cases, the evaluation of the fault registers show that the trip commands have been caused by the appearance of differential current only in one phase of the generator. In this section a real fault register is evaluated. This sample corresponds to a register of a real power plant, in which the unwanted trip command was caused by inrush currents of an adjacent transformer during it energizing process.

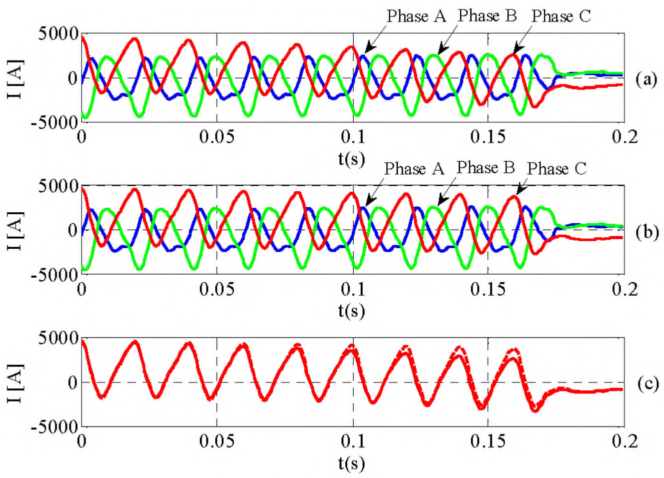

Figure 7. Neutral side currents (a), terminal side currents (b) and comparison between currents in phase C (c), in instantaneous value.

In Fig. 6, the currents of the neutral side and the currents of the terminal side are shown in RMS value. As a register obtain from a real protective system, the trip commands are shown at the bottom of the figure. The generator 87 trip command takes place at the center of the register.

In Fig. 7, the instantaneous neutral-side currents (Fig. 7 (a)) and terminal-side currents (Fig. 7 (b)) are shown. It can be noticed that the phase currents are different only in phase C. In Fig. 7 (c), the currents in phase C at both sides are compared, and it can be clearly observed that CT saturation in one of the CTs of this phase makes the currents to be different. The appearance of differential current at this phase causes the trip of 87.

In Fig. 8, the differential current of each phase is compared to its own restraining current. Furthermore, the position in the instant of the trip command at each phase is indicated using the same symbology than in Fig. 3. It can be clearly observed that only in phase C the differential current exceeds the operation current, which is also represented, using the parameter settings of the protection function at the real power plant. At the instant of the trip command, $I_{d,C}$ is in the operating zone, while $I_{d,A}$ and $I_{d,B}$ have much lower values.

V. Setting Consideration

The definition of the interception band through the secondary parameters has been performed, for this concrete case, by the values shown in (7).

$$
\begin{aligned}
I'_{s1} &= I_{s1} - 0.05pu \\
I'_{s2} &= I_{s2} \\
K'_1 &= K_1 \\
K'_2 &= K_2 - 10\%
\end{aligned}
\tag{7}
$$

The values of the secondary parameters are limited by the value of the general parameters of the differential protection. Entering the same values of general parameters and secondary parameters imply that the multi-phase criterion is mandatory

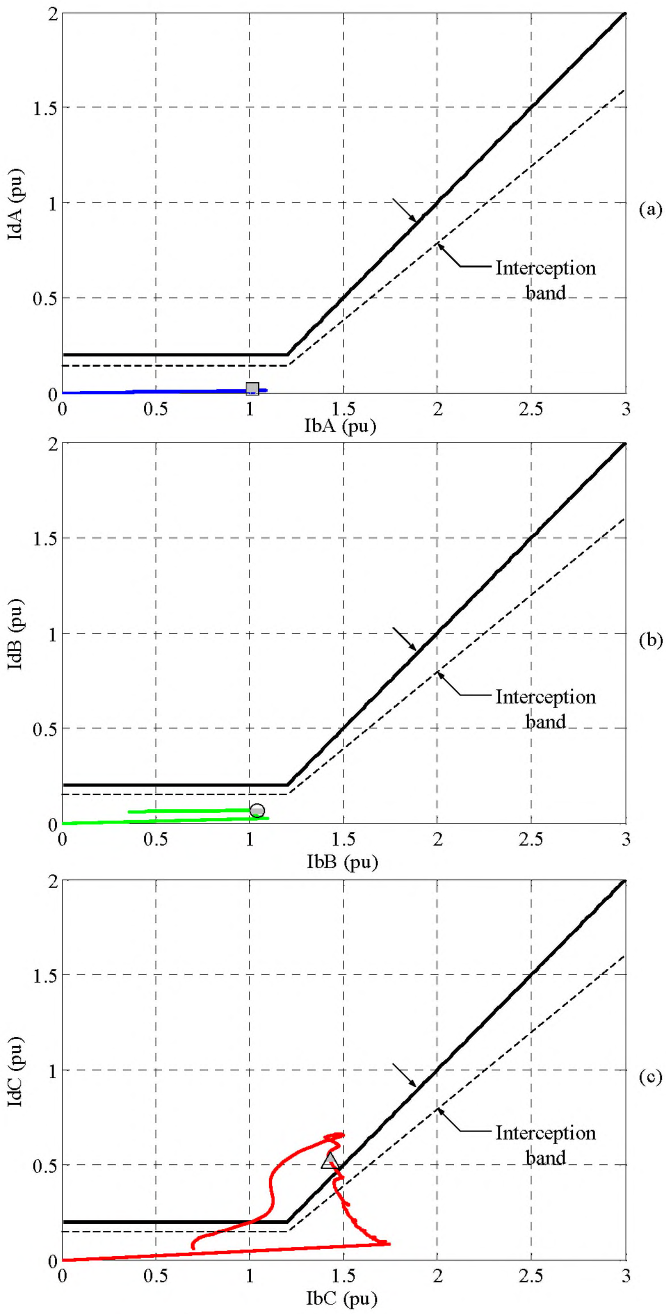

Figure 8. Real example of unwanted tripping operation

for generating a trip command, and no interception band is considered. In this way exceptional cases are excluded. The differential protection in this case is less sensible to individual CT saturation problems, but it is more dependable of the precision of the setting of the general parameters. Setting the secondary parameters to zero will enlarge the interception band to the whole restraining zone, disabling the multi-phase criterion.

Further research will be focused on the implementation of this algorithm in a real generator protective system, and obtaining the recommended value of the secondary parameters through laboratory tests.

VI. CONCLUSIONS

In this paper, the application of multi-phase criterion to the differential protection algorithm has been proposed for high-impedance grounded synchronous generators. This multi-phase algorithm is achieved by the definition of an interception band, through the setting of a secondary operation current. The multi-phase condition is achieved if at least two of the three differential currents exceed the secondary operation current. This algorithm has been checked in some fault registers of real power plants, where the trip command was caused by the saturation of an individual CT. Some setting consideration has been given for the definition of the interception band.

ACKNOWLEDGMENT

The authors wish to acknowledge the technical support of Alberto Barrado from Endesa Generación S.A. and Araceli Monje and Raphael Grollemund from Scheneider Electric.